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THIS ISSUE

Flow Properties of Lubricating Greases—Relationship of Apparent Viscosity

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FLOW PROPERTIES OF LUBRICATING GREASES —RELATIONSHIP OF APPARENT VISCOSITY

INTEREST has long centered on the possibilities of predicting the properties of lubricating greases from measurements giving results in fundamental rather than arbitrary units. A determination of the flow characteristics, for example, would be a step in this direction. Lubricating greases, however, are semi-solid or plastic materials and therefore do not flow like true liquids, such as lubricating oils, hence flow properties are difficult to measure.

With the advent of the Pressure Viscosimeter, fundamental measurements, in terms of apparent viscosities, have been made on greases. This article describes laboratory work which has attempted to relate apparent viscosity to low temperature torque, low temperature consistency and the dispensing characteristics of lubricating greases. The investigation points to the interesting possibilities of utilizing apparent viscosity determinations of greases to

(1) predict low temperature pumpability.

(2) make a more intelligent selection of greases to be handled in a given field dispensing system.

THE lubrication of any mechanical device in general involves separation of sliding or rotating metallic surfaces by a fluid film. For proper functioning and reducing wear and friction, the separating film must essentially float the surfaces involved and thereby prevent metal-to-metal contact. Lubricating oils and greases are commonly employed for this purpose.

When oils are selected for a particular application, consideration is given to the viscosity of the oil, i.e. light bodied oils are used for lightly loaded mechanisms while more viscous oils are chosen for heavy duty service. Lubricating oils are classed as Newtonian Liquids (fluids which obey certain fundamental laws of viscous flow) under ordinary conditions; their viscosity, or resistance to flow, can be accurately measured under a wide range of temperature and shear conditions.

Lubricating greases are mineral oils thickened with soap to a plastic or semi-solid consistency. Since their flow properties are somewhat different from those of oils, greases are known as Non-Newtonian materials.

If one places a lubricating oil in a container with a hole in the bottom, the oil will flow out. If a semi-solid grease is placed in this same container, a certain minimum pressure is required before flow begins. As originally manufactured, a grease is a viscous solid or semi-solid mass. Working or shearing the grease generally causes it to soften or work down; the more the working, the more the softening. However, some greases are more resistant to this phenomenon than other greases. In fact, recent research has resulted in lubricating greases offering a marked resistance to becoming thinner with working down, which is a distinct advantage where leakage is involved. In addition to the minimum pressure required to start the flow of the grease, it has also been found that the viscosity of a grease changes with the rate of shear. Temperature in general affects oils and greases in the same manner, both tend to thin down upon heating and to thicken upon cooling. There are, however, exceptions where certain materials are used in greases which may reduce thinning at increased

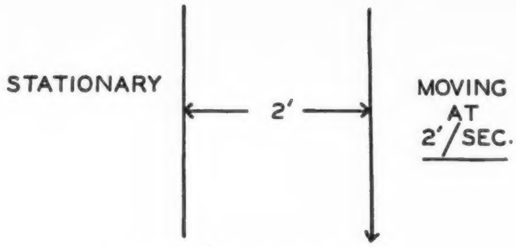


Figure 1—Rate of shear diagram.

temperatures.

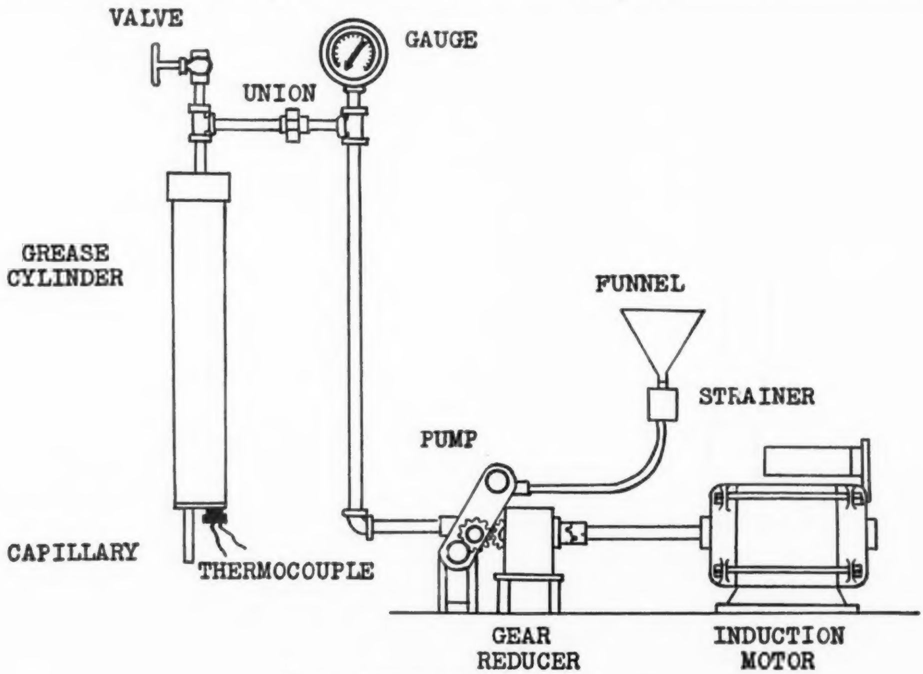
For purposes of discrimination, we speak of an oil's viscosity and a grease's apparent viscosity. Apparent viscosity varies with rate of shear as mentioned above. By way of explanation, the rate of shear may be defined as the ratio of the velocity of flow to the clearance between two parallel surfaces moving in opposite directions. If one considers the simple conditions as represented in Figure 1 of a stationary surface with another surface two feet away moving two feet per second, the shear rate of such a system would be one reciprocal second, which is generally written 1 sec. $^{-1}$.

It is the intent of this article to discuss some of the properties of greases as they relate to apparent viscosity. Flow properties, in particular, assume practical significance when one considers that such characteristics influence the torque and dispensing properties of lubricating greases. Before embarking on this discussion, however, it appears in order to present a resume of the equipment and method used to determine the apparent viscosity of greases.

Equipment for Measuring Apparent Viscosity

The measurement of apparent viscosity of greases requires special equipment. To simulate actual service conditions, the measuring instrument should permit shear rates to be varied over a large range. Many instruments, such as the rotating viscosimeters, have been unsatisfactory for this reason. Best results have been obtained with the capillary-tube viscosimeters, such as that utilized by Arveson.[1] Such instruments give results in absolute units rather than arbitrary units such as obtained with the Saybolt tube or the ASTM Penetrometer. Even so, the early capillary-tube instruments were expensive and rather complicated, hence, of limited utility. Recently, however, a simplified version of the capillary-tube type of instrument known as the Pressure Viscosimeter has been developed which is suitable for routine apparent viscosity determinations.[2] This new equipment has been used for all the apparent viscosity determinations discussed in this article.

A diagrammatic sketch of the Pressure Viscosimeter is shown in Figure 2. An induction type electric motor drives a constant volume displacement Zenith pump through a 200 to 1 gear speed reducer. The pump delivers hydraulic oil to the top



Courtesy of Standard Oil Development Company

Figure 2—Details of pressure viscosimeter.

of a floating piston which in turn, rests on the grease in the cylinder. The hydraulic oil is pumped at a definite and constant rate thereby forcing the grease through the capillary at a constant rate. Pressures developed are measured by Bourdon type gages connected to the hydraulic system as shown. For different shear rates, different capillaries are used and/or the gears attached to the pump are changed. Two different size gears are available for the latter purpose.

To facilitate investigations at various temperatures, the Pressure Viscosimeter is set up in a temperature cabinet capable of control over the range of minus 90°F. to plus 220°F. The cabinet is heated electrically or cooled by means of dry ice and temperature can be regulated within plus or minus one degree F. Figure 3 shows the outside view of the equipment employed. It will be noted that the entire end of the sub-zero test cabinet is constructed in the form of a hinged door which can be swung open for ready access to the equipment located in the cabinet's interior. The drive motor and reduction gear for the Pressure Viscosimeter are located on the outside of the cabinet in order that this part of the equipment can be operated under ordinary room temperature conditions rather than under the extreme conditions which may prevail in the cabinet's interior. An extension shaft passing through the cabinet wall connects the reduction gear to the constant volume pump. Figure 4 is an interior view of the cabinet. In the left foreground is visible the constant volume displacement pump, the hydraulic oil lines, the pressure gage and grease cylinder. One capillary tube is shown affixed to the discharge end of the cylinder while the remaining capillaries are arranged at the right of the photograph. These various capillary tubes, it will be recalled, are used to vary the shear rate of the grease, and have the following dimensions:

Capillary No.	*Length, inches*
1	6.080
2	3.880
3	2.920
4	2.400
5	1.920
6	1.600
7	1.000
8	0.720

Each capillary has a length to diameter ratio of 40 to 1, this relationship being held constant to improve accuracy of measurements. Grease temperatures are measured by means of a thermocouple located on the discharge end of the cylinder. In the background of the illustration are seen two calcium chloride racks which absorb moisture and prevent fogging of the cabinet interior when temperatures are lowered. At the extreme rear is seen the dry ice compartment and air circulating system for lowering the temperature.

Principle of Pressure Viscosimeter

The pressure required to force grease at a constant, known rate through a capillary of known length and radius is determined. The apparent viscosity is then calculated by means of Poiseuille's equation

$$\eta = \frac{\pi P R^4}{8 L \, v/t} \qquad \text{(I)}$$

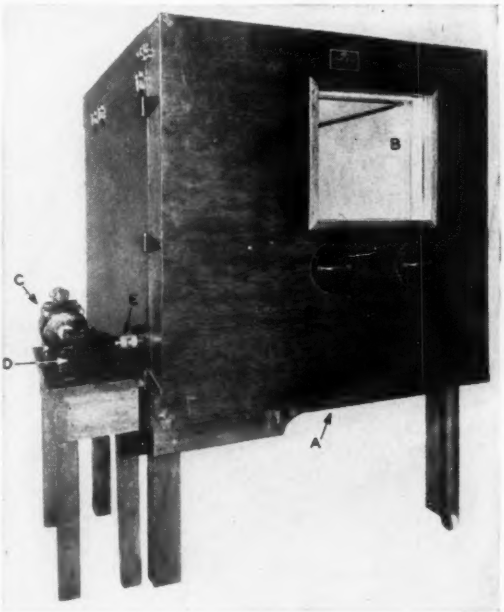


Figure 3—Exterior view of low temperature cabinet.

A—Hinged door; B—Observation window; C—Drive motor; D—Reduction gear; E—Extension shaft.

where

η = apparent viscosity (poises)
P = pressure (dynes/cm^2)
R = radius of capillary (cm)
L = length of capillary (cm)
v/t = cc/sec flow rate

The rate of shear is calculated by the following expression where the letters refer to the same quantities as above

$$S \text{ (shear rate)} = \frac{4\,(v/t)}{\pi R^3} \qquad \text{(II)}$$

Having described the equipment and method of determining apparent viscosity, our next concern is how such information can be utilized along practical lines. It is of interest, in this connection, to consider the relationship of apparent viscosity to the low temperature properties of greases. Before

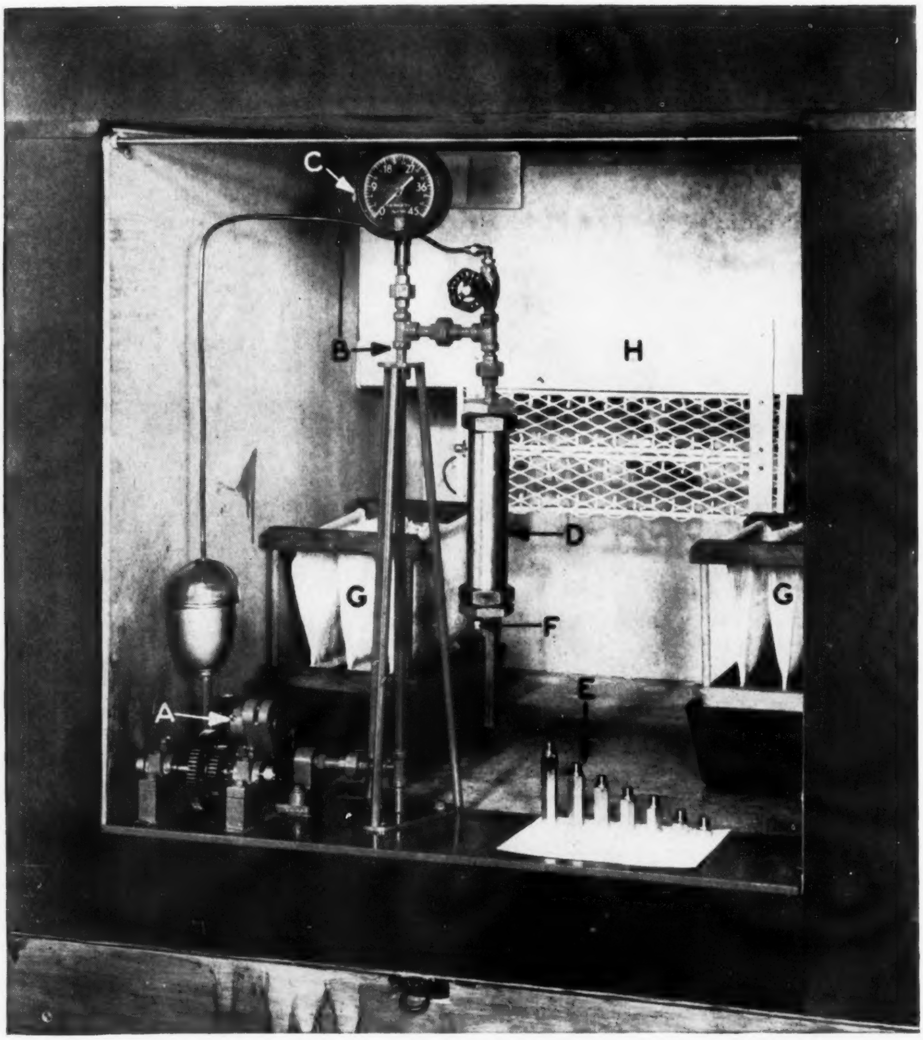


Figure 4—Interior view of low temperature cabinet.

A—Constant volume displacement pump; B—Hydraulic oil lines; C—Pressure gage; D—Grease cylinder; E—Capillary tubes; F—Thermocouple connection; G—Calcium chloride drying racks; H—Dry ice compartment.

doing this, however, some space will be devoted to how low temperature torques of greases are measured.

Low Temperature Torque Measurements

During World War II the measurement of torque characteristics of aircraft control bearing greases at low temperatures received considerable attention. The laboratories of the Armed Forces faced with this problem developed a method wherein the time required for a grease-lubricated small ball bearing (size No. 204) to complete one revolution under a definite torque load and at a definite reduced temperature was determined. This procedure was incorporated into a specification with definite limits set for torque.[3]

Concurrent with the establishment of specifications, other groups were actively engaged in refining the type of equipment and the detailed procedure for determining low temperature torques. The result of this work was the method and apparatus prescribed by the Annular Bearing Engineers' Committee—National Lubricating Grease Institute Cooperative Committee.[4] Additional work is being done by this group to improve reproducibility still further. Figure 5 is an exterior view of the test apparatus. It consists of an insulated chest mounted on a revolvable pedestal. An opening at the top leads to an interior finned copper container filled with dry ice and isopropyl alcohol for re-

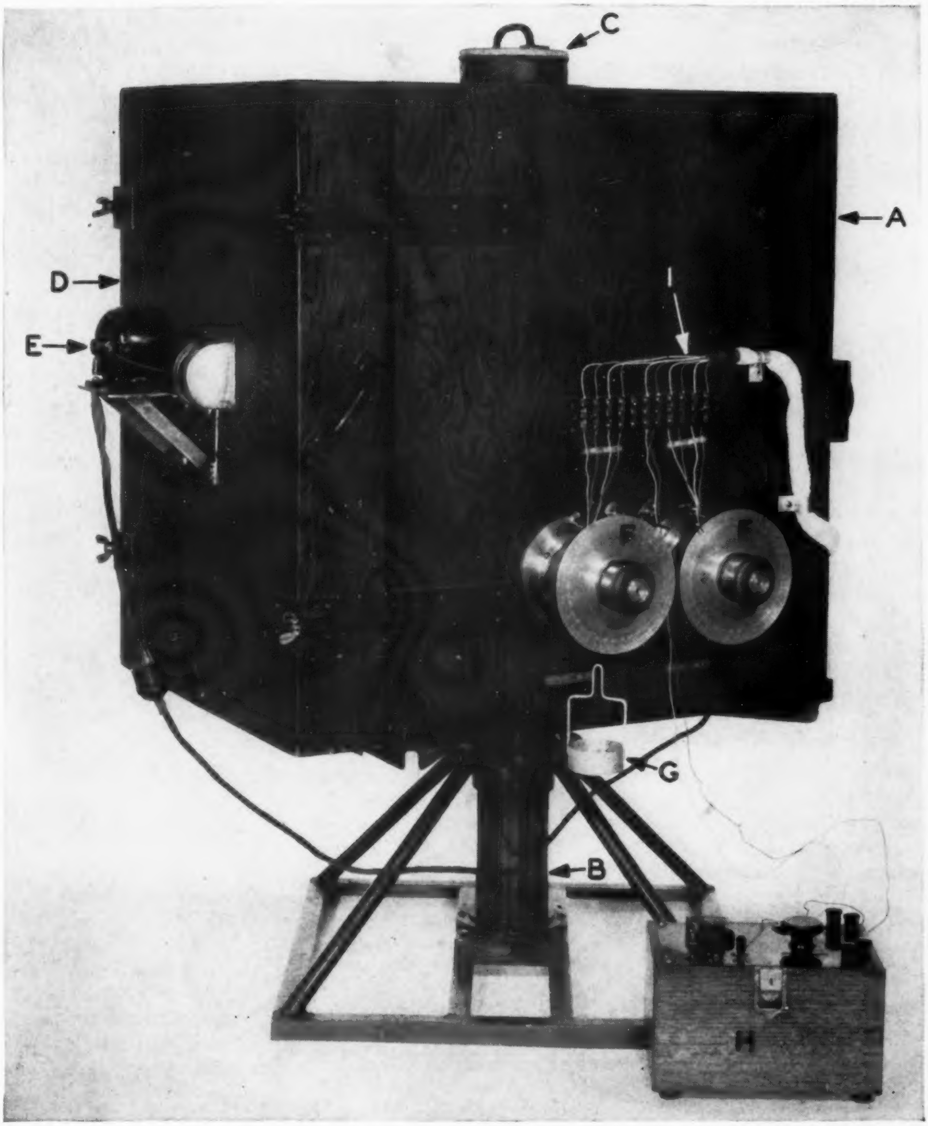


Figure 5—Exterior view of ABEC-NLGI low temperature torque apparatus.

A—Insulated chest; B—Pedestal; C—Opening for refrigeration chest; D—Removable door; E—Motor for circulating air fan; F—Bearing test spindles; G—Weight pan; H—Potentiometer; I—Thermocouple leads.

frigeration. The end door is removable and carries a high speed fan for circulating interior air. Into opposite sides of the chest are fixed two bearing test spindles, which will be described subsequently in more detail. Torque is applied by adding a known weight to a suspended pan attached to the outer end of the spindle. A potentiometer connected by thermocouples to the test bearings provides for temperature measurements.

A detailed drawing of the test bearing assembly is included as Figure 6. The spindle and quill are made from a combination of bearing steel and synthetic material of low heat conducting properties. That part of the assembly which extends outside the cold chest contains the outboard bearing and a spool for applying torque loads. The other end of the spindle carries the test bearing.

Figure 7 is the interior view of the torque apparatus showing the refrigeration chest and arrangement of the test bearing assemblies.

Measurements are made of the time required in seconds for the test bearing to make one complete revolution under a definite applied load (torque). Determinations are customarily made over a range

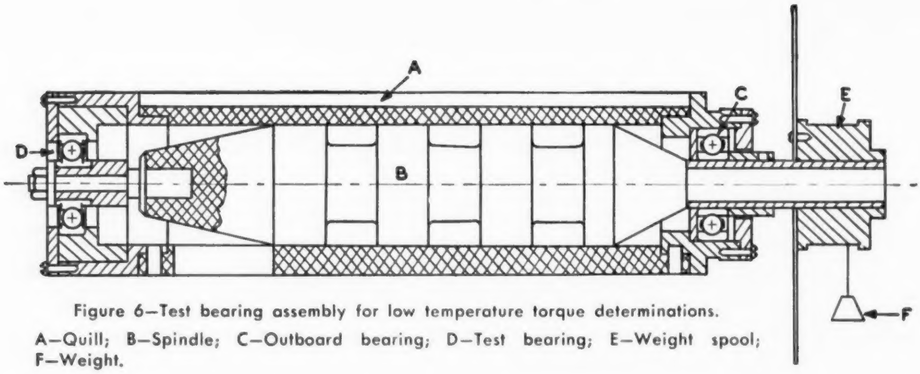


Figure 6—Test bearing assembly for low temperature torque determinations. A—Quill; B—Spindle; C—Outboard bearing; D—Test bearing; E—Weight spool; F—Weight.

of applied loads to give a range of time intervals for one revolution. In work conducted at the Norma-Hoffmann Bearings Corporation Laboratory, F. L. Wright[5] found that the results of such tests can be conveniently expressed as a "Plasticity Number" (PN) obtained by multiplying the applied torque load by the seconds per revolution obtained in a No. 204 ball bearing. Limit on time per revolution restricts the rate of shear and improves the reliability of this type test.

Relation of Apparent Viscosity to Low Temperature Torque

The procedure described in the foregoing section is fairly reproducible. It is evident, however, that since the time per revolution varies among greases, the rate of shear varies and consequently the apparent viscosity of the greases differ during the test. Tests of this type do not give results in fundamental units, hence the results are only strictly applicable to the same kind of bearing containing the same amount of grease as used in the test. As a natural recent consequence, considerable interest developed in the possible use of Pressure Viscosimeter data as a means of determining the torque characteristics of a grease. This was prompted by Arveson's conclusion that the apparent viscosity of a grease approaches, at increasingly high shear rates, a value higher than, but of the same order of magnitude as that of the mineral oil in the grease.[1]

To establish the relationship of apparent viscosity to bearing torque, as measured by Plasticity Number, a series of six greases was prepared and investigated. These products were of relatively smooth, buttery texture of the type found from experience to be best suited for the lubrication of aircraft control bearings over a wide range of extreme temperatures. In order to allow for operation at sub-zero temperatures, it was necessary to use mineral oils of low viscosity in compounding these greases. Greases were made from three different viscosity oils. From each oil, two greases were made, one meeting NLGI* No. 2 grade penetration requirements while a second was prepared to meet the softer NLGI No. 1 grade consistency. Pertinent tests on the six greases are given in Table I.

The apparent viscosity of these six greases was determined at various shear rates and at temperatures of 77°F., minus 40°F., minus 67°F., and minus 80°F. Figure 8 is a plot of apparent viscosity vs. shear rate for the NLGI No. 2 grade product made from a 40 S.U. viscosity at 100°F. mineral oil and is typical of such data obtained on all six greases. In general, the data substantiate the statement made at the outset of this article that the flow of a grease varies with shear and temperature. Specifically, the apparent viscosity decreases with increase in shear rate and increases rapidly as the temperature is lowered. For a product containing a specific mineral oil, the apparent viscosities are higher in every case for greases of NLGI No. 2

*—National Lubricating Grease Institute

TABLE I

DATA ON CONTROL BEARING GREASES

NLGI Grade	2	1	2	1	2	1
ASTM Penetration, Worked at 77°F.	276	333	276	315	275	331
Approx. Viscosity of Contained Oil, (S.U. at 100°F.)	40	40	50	50	60	60
Soap Content, %	20.3	17.1	18.0	14.2	16.9	13.0

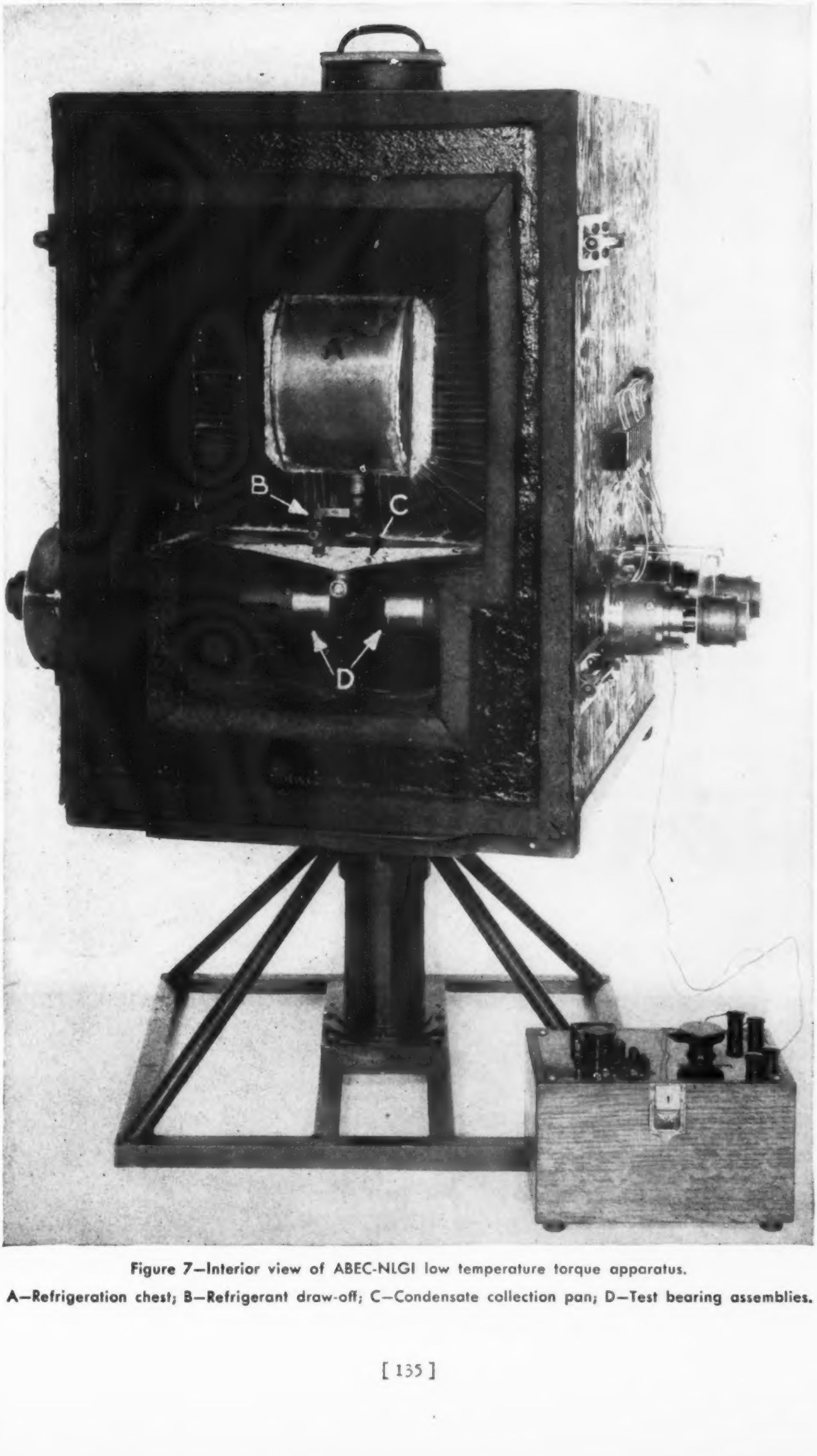


Figure 7—Interior view of ABEC-NLGI low temperature torque apparatus.

A—Refrigeration chest; B—Refrigerant draw-off; C—Condensate collection pan; D—Test bearing assemblies.

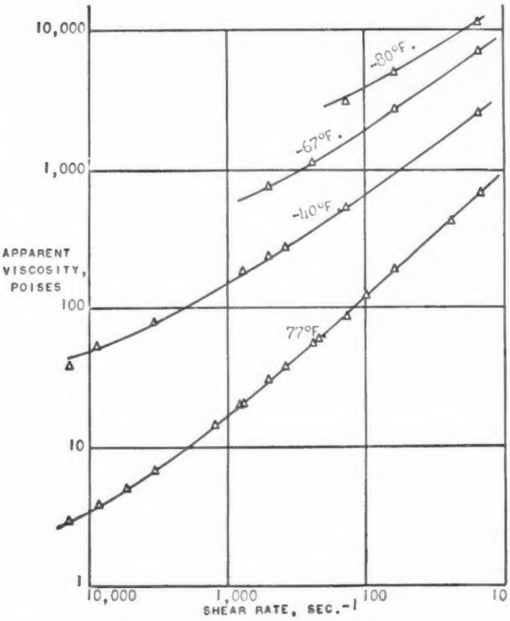


Figure 8—Apparent viscosity versus shear rate for NLGI No. 2 grade aircraft control bearing grease made from 40 S. U. viscosity at 100°F. mineral oil.

consistency than those of the softer NLGI No. 1 consistency.

When Plasticity Number determinations were made on the six greases, the results shown in Table II were obtained (p. 138).

Using an acceptable upper limit for Plasticity Number of 30,000 (15 seconds per revolution × 2000 gm-cm load), the above greases are indicated to give satisfactory operation down to temperatures as follows:

Viscosity of Oil, S.U. at 100°F.	*40*	*50*	*60*
NLGI Grade 1	—93°F.	—72°F.	—65°F.
2	—85°F.	—65°F.	—58°F.

The above method of reporting the low temperature properties of greases in terms of the lowest usable temperature rather than Plasticity Number is currently gaining favor since such data are more readily understandable by the consumer.

A plot of all the apparent viscosity values and Plasticity Numbers on the six greases at all temperatures on a log-log chart, as shown in Figure 9, indicates a general relationship between apparent viscosity and PN. This relationship can be expressed by the equation.

$$\log \text{apparent viscosity} = a \log \text{Plasticity No.} + b \qquad \text{(III)}$$

where b depends on the shear rate at which the apparent viscosity is determined and a is a constant independent of shear rate but presumably dependent on the dimensions of the apparatus.

Although the relationship is somewhat rough, it is indicated that the apparent viscosity can serve to define the low temperature torque characteristics of a grease. For instance, accepting the arbitrarily selected specification requirement of 30,000 maximum Plasticity Number at minus 67°F., an apparent viscosity upper limit of about 430,000 centi-

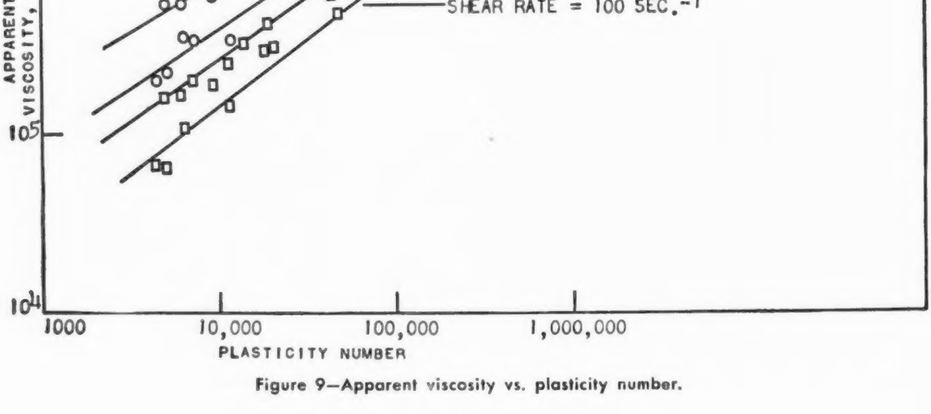


Figure 9—Apparent viscosity vs. plasticity number.

stokes (4000 poise) at 100 sec. $^{-1}$ or 1,200,000 centistokes (10,000 poise) at 15 sec. $^{-1}$ and minus 67°F. should satisfactorily define the grease characteristics instead of a torque test requirement.

Relation of Apparent Viscosity to Penetration

The regular ASTM penetrometer, shown in Figure 10, is standard equipment used for grease penetration or consistency measurements. Essentially, the method consists of bringing the tip of the penetrometer cone (made to definite weight and dimension specifications) in contact with the smoothed surface of a grease sample, releasing the plunger for a definite time interval and allowing the cone to penetrate into the grease sample. Depth of penetration is read on the dial. Penetrations may be determined either on the as-received (unworked) basis or on the worked basis, in which latter instance the sample is placed in the ASTM worker and a perforated plunger passed a total of 60 full double strokes through the grease. Greases are classified by the NLGI scale for consistency in accordance with their worked penetration. Soft greases have higher penetration values since the cone will penetrate farther into a soft grease than into a hard grease.

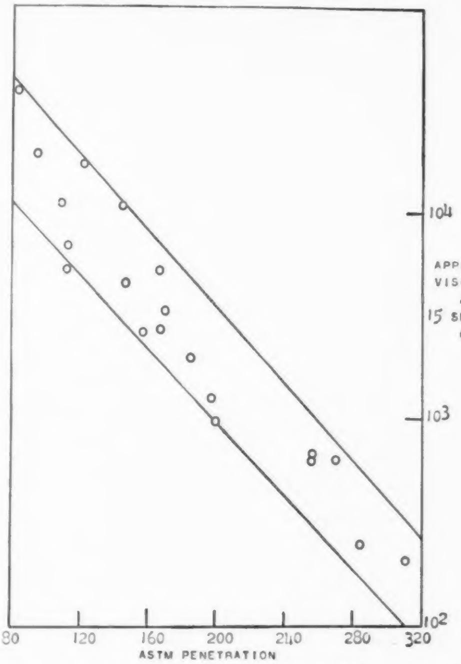


Figure 11—Apparent viscosity vs. ASTM penetration.

Like many other grease tests, penetration depends on temperature. For this reason, penetration measurements are customarily made at 77°F. (± 1°F.). On the other hand, advantage has been taken, in certain instances, of the fact that greases harden with lowering of temperature to predict their low temperature properties. It seems appropriate, therefore, to consider the relationship of ASTM penetration to apparent viscosity in the present study.

Worked penetrations [6] were obtained at 77, minus 40, minus 67, and minus 80°F. on the six control bearing

Figure 10—ASTM penetrometer.
A—Indicating dial; B—Penetrometer cone; C—Plunger release; D—ASTM worker.

TABLE II

PLASTICITY NUMBER OF CONTROL BEARING GREASES

(2000 gm-cm torque)

NLGI Grade	*Viscosity of Oil, S.U. at 100°F.*	*Plasticity Number* —40°F.	—67°F.	—80°F.
2	40	....	9,000	21,000
1	40	....	5,000	11,000
2	50	3,000	37,000	180,000
1	50	2,000	20,000	80,000
2	60	5,000	100,000	600,000
1	60	2,600	40,000	240,000

greases mentioned in the preceding section. A plot of these penetration data against apparent viscosity on a semi-log graph is shown in Figure 11. It will be noted that the relationship between apparent viscosity and ASTM penetration is rough, at best, and not sufficiently exact to permit the use of penetration data in place of apparent viscosity. For example, the plot indicates that a grease of 180 penetration may have an apparent viscosity ranging from 1500 to over 5000 centistokes.

Relation of Apparent Viscosity to Pumpability

This article has brought out that the method employed for determining apparent viscosities consists of forcing the grease under pressure through a small diameter tube. Fundamentally this duplicates the conditions existing in any conventional system or equipment used to dispense lubricating greases in the field. It is a natural consequence that investigators have attempted to relate apparent viscosity to grease pumpability, and considerable work has been done in this field.(7)

The question often arises as to whether a given dispensing system, under specific conditions existing in field installations, will handle the grease best suited for that purpose. Such questions are difficult to answer inasmuch as many factors, such as distance, temperature, pressure, physical lay-out, equipment condition, etc., complicate a ready solution. Recommendations are therefore tempered by past experience with a similar set of conditions, or, lacking such guidance, the particular piece of equipment involved is transported to the laboratory and tested with the selected grease under simulated field conditions. This, obviously, provides only limited information which may or may not prove beneficial in solving other dispensing problems. For this reason, it was considered pertinent to determine if the dispensing characteristics, or pumpability of a grease could be established by a laboratory method which would give the results

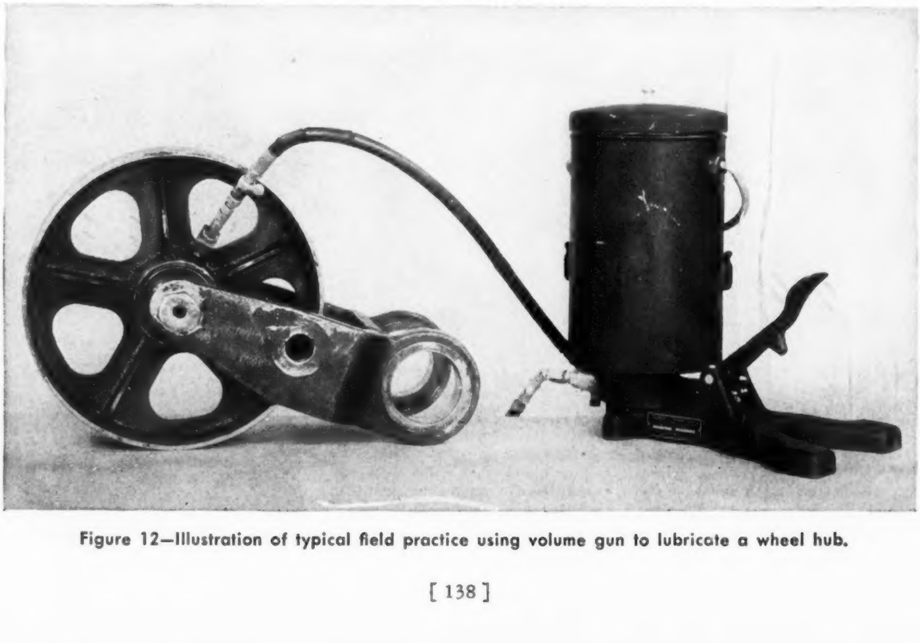


Figure 12—Illustration of typical field practice using volume gun to lubricate a wheel hub.

TABLE III

DATA ON GREASES FOR PUMPABILITY STUDIES

Grease	*A*	*B*	*C*	*D*	*E*
Type Contained Oil	*Napthenic*	*Mixed Napthenic — Paraffinic*			*Paraffinic*
Viscosity of Contained Mineral Oil (S.U. at 100°F.)	605	197	601	1061	615
Sodium Soap, %	10.8	19.6	18.1	18.5	14.3
Penetration at 77°F., ASTM — Unworked	289	225	233	282	233
Worked	278	258	257	291	262

in terms of fundamental units, such as apparent viscosity, and more reproducibly than tests conducted in the dispensing equipment itself.

The Volume Gun, illustrated in Figure 12, was selected as a representative type of grease dispensing gun for such an investigation. This gun is of conventional type, having a one-direction forced stroke with a foot pedal returned to the loaded position by a spring. The grease is forced by gravity to the suction inlet. In all the work presented in this discussion, a 150 pound load was applied to the food pedal and the pump was connected to a standard $\frac{1}{4}$ inch i.d., $7\frac{1}{2}$ foot synthetic hose. Pumpability was measured in terms of grams of grease delivered per second.

Five sodium soap greases of about No. 2 NLGI grade were studied. Information on these greases is recorded in Table III.

Apparent viscosities at shear rates of 15.04 to 8750 sec. $^{-1}$ (1) and pumpabilities of the five specimen greases were determined at 20°, 40°, and 77°F. Data on two of these greases, plotted against temperature, are shown in Figure 13. It is seen that the grease with the best pumpability characteristics has the lowest apparent viscosity. This relationship would hold if we plotted all the greases in similar manner. Thus, a definite correlation is shown to exist between apparent viscosity and pumpability. Plotting the pumpability data on all the greases at all temperatures against the corresponding apparent viscosity at a shear rate of 15.04 sec. $^{-1}$ on a log-log scale, a straight line is obtained as shown in Figure 14, although there is some scattering of the points.

It makes little difference whether one plots the apparent viscosities for a low shear rate such as

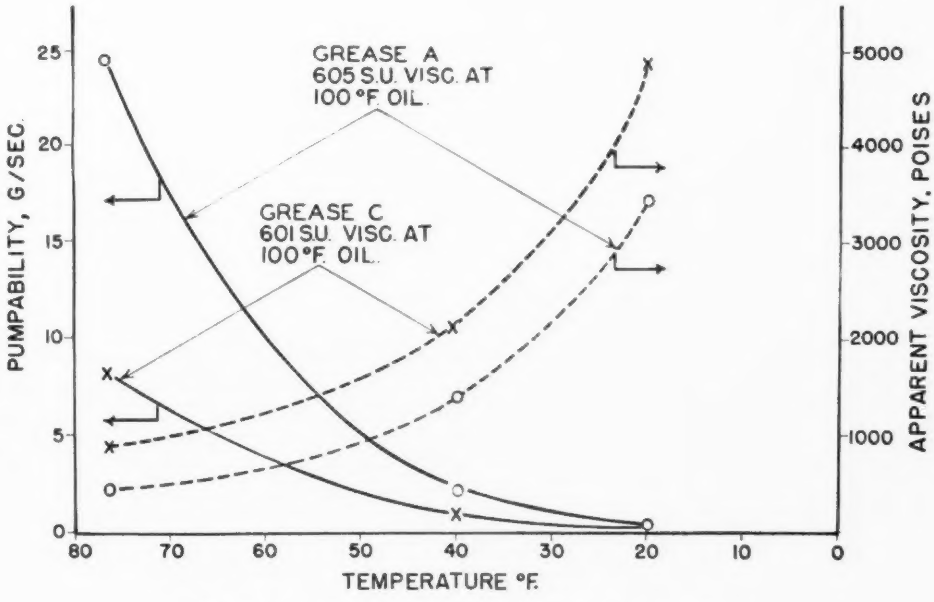


Figure 13—Pumpability and apparent viscosity vs. temperature.

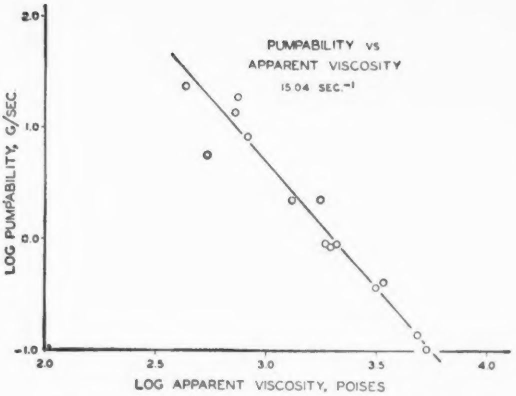


Figure 14—Pumpability vs. apparent viscosity.

15.04 sec. $^{-1}$ or some higher shear rate as shown in Figure 15. The only point is that the band (measure of scattering of the points from the best line which can be drawn to show the relationship) is indicated to be better when the apparent viscosity data are obtained at relatively low shear rates. The equation expressing the relationship between apparent viscosity and pumpability (both taken at the same temperature) is:

log pumpability $= a + b$ log apparent viscosity where a and b are constants. (IV)

Summary

Summarizing, it seems that apparent viscosity data as obtained from Pressure Viscosimeter determinations may be useful in predicting the low temperature performance of lubricating greases. On the other hand it is improbable that such data could be relied upon to establish performance at high temperatures owing to oil bleeding, leakage, drastic texture changes, etc., many greases undergo under such conditions. Investigation of the flow properties of greases at higher shear rates (more nearly those existing in a rapidly rotating bearing) than obtainable with the herein discussed Pressure Viscosimeter equipment, affords a fertile field for future research. A much better analysis of the friction characteristics of greases would result if such data could be made available.

This study further points to the possibility of relating the dispensing character, or pumpability, of greases to apparent viscosity. The usefulness of this relationship could be expanded if dispensing equipment manufacturers were in a position to specify the upper limit of apparent viscosity of the lubricant which their equipment could handle satisfactorily under a given set of conditions. The grease manufacturer could then, from apparent viscosity measurements, determine what greases the particular dispensing equipment can handle, and from these the proper grease for the particular application could be selected. Steps have been taken to initiate such a cooperative program and this endeavor should gain impetus with the passage of time.

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(4) ABEC-NLGI Technical Bulletin No. 1 — "Method for Determination of Low Temperature Torque Characteristics of Greases in Anti-Friction Bearings."

(5) Private Communication, dated November 11, 1942 from F. L. Wright, Norma-Hoffmann Bearings Corporation.

(6) Tentative Method of Test for Consistency of Lubricating Greases and Petrolatum — A.S. T.M. Designation: D217-44T.

(7) Symposium on Pumpability of Greases and Delivery Characteristics of Dispensing Equipment, dated March 1, 1947, held during 14th Annual Convention of National Lubricating Grease Institute.

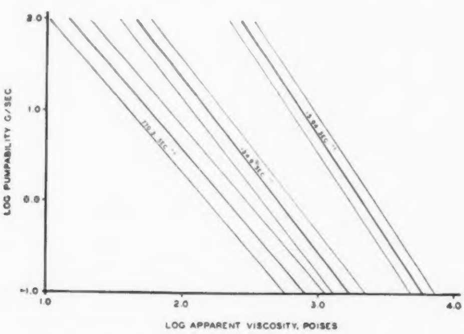

Figure 15—Pumpability vs. apparent viscosity.

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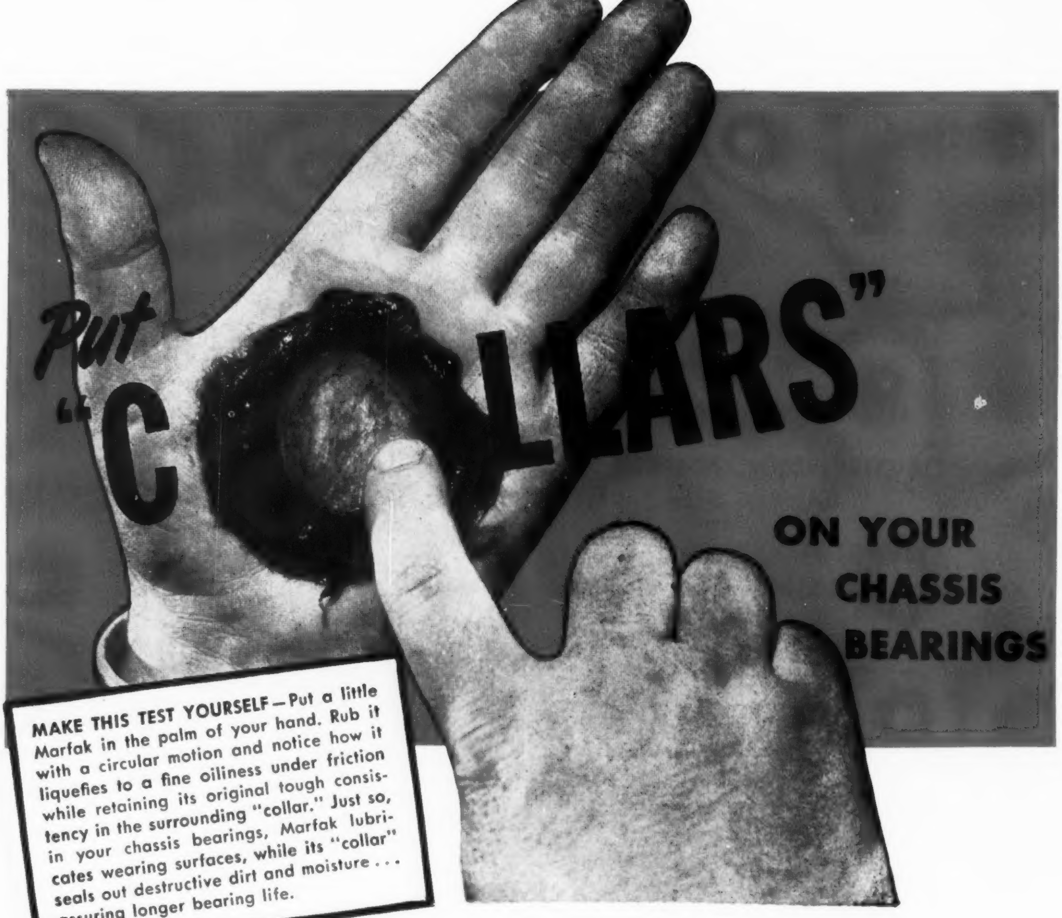
Put
"COLLARS"
ON YOUR
CHASSIS
BEARINGS
MAKE THIS TEST YOURSELF—Put a little Marfak in the palm of your hand. Rub it with a circular motion and notice how it liquefies to a fine oiliness under friction while retaining its original tough consistency in the surrounding "collar." Just so, in your chassis bearings, Marfak lubricates wearing surfaces, while its "collar" seals out destructive dirt and moisture . . . assuring longer bearing life.